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Evaluation of the Energy Performance of Transparent Photovoltaics for Building Windows in Tropical Climates

Laurentius Kevin Hendinata [1, 2,] *, Ribka Prilia [1] , Ahmad I. R. Fikri [1] , Michael A. Suprapto [1] , Nur A. Siddiq [1]

[1] Department of Nuclear Engineering and Engineering Physics, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika No. 2, Sleman, Yogyakarta 55281, Indonesia
[2] WAVES Erasmus Mundus Joint Master Program, University of Coimbra - Portugal, Universitat Politècnica de València - Spain, Aix-Marseille Université, and Ecole Centrale Marseille, France

*Corresponding Author: kevinhendinata@mail.ugm.ac.id

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Abstract

Windows are a critical factor in enhancing energy efficiency in buildings, especially in tropical climates, where they are exposed to high-intensity sunlight. The incorporation of transparent photovoltaics using various PV technologies offers the opportunity for windows to harness solar energy for building purposes. The energy-saving benefits of using transparent photovoltaics have been extensively analyzed in various countries, but there is still a lack of comparative studies focusing on tropical countries. Our study aims to fill this gap by assessing the potential of transparent photovoltaics in enhancing energy efficiency in buildings located in Jakarta, Singapore, Kuala Lumpur, Rio de Janeiro, and Kotoka. We developed an energy consumption model located in a tropical climate, utilizing the EnergyPlus software. The simulation results clearly indicate that integrating photovoltaics into the building is particularly advantageous due to consistent solar radiation and the need for cooling and ventilation, resulting in a substantial up to 59.3% reduction in total energy consumption. As a contribution, our research underscores the potential of transparent photovoltaics to revolutionize building energy efficiency in tropical climates, providing significant energy savings and promoting sustainable building practices. Addressing climate challenges, such as temperature and humidity management, necessitates the utilization of advanced materials and design strategies. Additionally, policy challenges encompass the requirement for favorable policies, incentives, and well-defined guidelines for the installation of PV windows.

Keywords:
transparent photovoltaics, building windows, energy consumption, EnergyPlus model, passive design

1. Introduction

In recent years, there has been a notable surge in both research endeavors and practical implementations concerning building integrated photovoltaics (BIPV). BIPV entails the integration of photovoltaic materials into distinct components of building envelopes, such as roofs and facades, as a substitute for conventional building materials (Jelle et al., 2012; Yu et al., 2021). The core principle of BIPV revolves around harnessing the potential of photovoltaic power generation technology, capable of transforming solar energy into electrical energy, with the overarching objective of meeting the energy demands of buildings (Do et al., 2017; Jelle et al., 2012; Martín-Chivelet et al., 2022).

The installation of BIPV encompasses a range of substantial impacts and benefits, one of which is the provision of energy efficiency within the building. These effects stem from the performance-related prerequisites for BIPV modules and systems, which influence the energy consumption of the building. These prerequisites encompass the electrical performance of BIPV, the level of thermal insulation, the solar heat gain coefficient, and the optical properties (Martín-Chivelet et al., 2022).

An intriguing application of BIPV is their integration into windows. Unlike the conventional installation of PV panels on rooftops, the utilization of BIPV on façades necessitates careful consideration of the façade's orientation (Arnaout et al., 2020; Brito et al., 2017; Mangkuto et al., 2023). This is due to the varying solar radiation and daylight availability experienced by different orientations. Moreover, the PV panels used in BIPV applications on façades need to maintain a certain level of transparency and transmittance to allow sufficient daylight to enter the building for illumination purposes. Therefore, unlike traditional PV technology, which primarily focuses on maximizing light absorption for power conversion efficiency (PCE), BIPV on façades must achieve high PCE while considering the overall performance of the building (Basher et al., 2023; Mangkuto et al., 2023; Roy et al., 2020).

The tropical climate provides an ideal setting for the integration of BIPV, benefiting from the consistent solar radiation available throughout the year (Abdullahi et al., 2021; Mangkuto et al., 2023). In these regions, characterized by hot and humid conditions, there is a substantial need for cooling and ventilation in urban areas, resulting in a significant proportion (30–50%) of electricity consumption (T. Chen et al., 2022). The tropical region experiences a fairly constant climate, with abundant rainfall, high humidity and temperatures throughout the years (Rababah et al., 2021). As a result, reducing emissions, specifically carbon dioxide emissions, is a critical objective in overall emission reduction strategies for tropical countries. The widespread use of extensive windows in building designs further enhances the suitability of BIPV technology in tropical regions. This favorable combination highlights the considerable potential for implementing BIPV in tropical buildings. However, a comprehensive assessment of BIPV's efficacy in such environments necessitates a thorough evaluation of its energy performance within the specific climatic conditions prevalent in tropical regions.

This study aims to evaluate the energy performance of transparent photovoltaics applied to building windows in a tropical climate, considering their potential for installation in buildings in tropical areas. The energy performance of various BIPV windows has been extensively investigated in various locations, including Tanzania (Joseph et al, 2019), Texas (Do et al, 2017), China (Li et al, 2021), Birmingham (Liu et al, 2020), Melbourne (Panagiotidou et al, 2021), Spain (Romaní et al, 2021), Minneapolis (Ulavi et al, 2014), and New York (Wheeler et al, 2022). However, studies comparing the performance of BIPV windows across multiple countries are still limited, as highlighted by Hassan et al (2022) for Dhaka, Abu Dhabi, and Oslo. Therefore, our study aims to fill this gap by pioneering efforts to compare the performance of BIPV windows in four tropical climates, namely Jakarta, Singapore, Kuala Lumpur, Rio de Janeiro, and Kotoka.

In comparison to existing studies, this research provides a study and comprehensive analysis of their characteristics and parameters. This study adopts a solar cells model to be applied to BIPV windows, highlighting their impact on its optical and energy performance. The focus of this study is oriented to an energy perspective, limiting the discussion to lighting and thermal performance. By specifically examining the context of tropical buildings, the contribution of our study is to explore the potential of BIPV in optimizing energy efficiency and promoting sustainability. The evaluation encompasses various factors, such as electrical performance, thermal insulation capabilities, solar heat gain coefficient, and optical properties. Finally, discussions are added to provide insights for architects, building designers, and policymakers seeking to promote sustainable building practices in these regions. Through an analysis of these aspects, we provide valuable insights into the feasibility and effectiveness of transparent photovoltaics for building windows in tropical climates. The findings of this study have the potential to enhance our understanding of the energy-saving capabilities and overall performance of transparent photovoltaics in tropical building environments. Additionally, the outcomes can serve as a basis for developing strategies to integrate BIPV technologies into tropical building designs, fostering energy-efficient practices and sustainable solutions for the construction industry.

2. Methods

2.1 BIPV Windows: Characteristics and Parameters

BIPV windows are commonly recognized as semi-transparent photovoltaics in numerous literature sources due to their characteristic semi-transparency. The solar cells employed in BIPV windows encompass various types, including c-Si (crystalline silicon), a-Si (amorphous silicon), CdTe (cadmium telluride), as well as emerging solar cell technologies like poly-Si (polycrystalline silicon), dye-sensitized solar cells (DSSCs), and perovskite solar cells. For its application as building windows, a series of PV cells are typically sandwiched between two glass sheets, as shown in Figure 1.

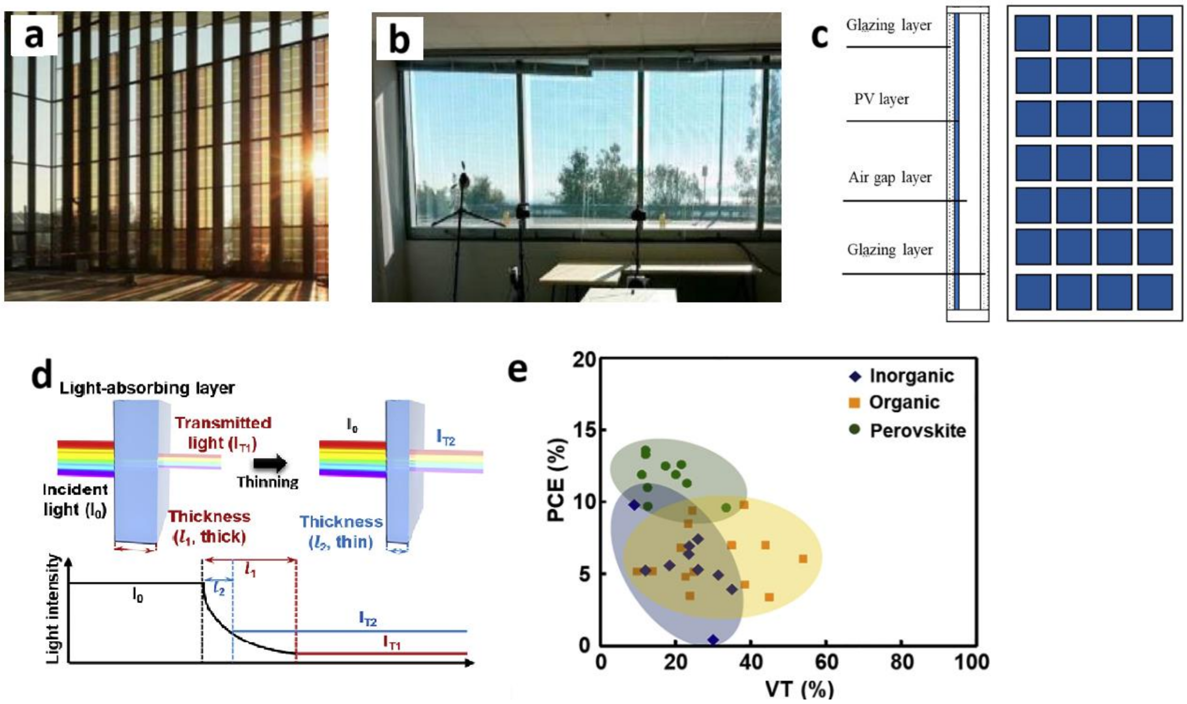

Figure 1. (a) Transparent glazing installation with dye-sensitized solar cells (Lee et al., 2020), (b) Semitransparent glazing installation with c-Si solar cell strips (Lee et al., 2020), (c) Semitransparent PV window module layer configuration (Li et al., 2021), (d) Illustration of light entering the module which is absorbed and transmitted by module (Lee et al., 2020), and (e) Power Coverssion Efficiency (PCE) on average Visible Transmittance (%) of organic, inorganic and perovskite thin films (Lee et al., 2020).

BIPV windows can be obtained in diverse configurations of glass types, thicknesses, strengths, and transparency levels, collectively exerting influence over key characteristics such as the U-factor, Solar Heat Gain Coefficient (SHGC), solar transmittance (τ_{solar}), visible transmittance (τ_{vis}), and energy conversion efficiency (Baenas & Machado, 2017; Do et al., 2017; Gueymard & duPont, 2009; Sánchez-Palencia et al., 2019). These properties, in turn, impact various aspects of building loads, encompassing heating, cooling, and lighting requirements, as well as the generation of electricity.

The SHGC quantifies the amount of solar energy that enters a room directly through the window (F. Chen et al., 2012; Yu et al., 2021). On the other hand, the U-value represents the rate of heat gain or loss through the window due to temperature differences between the indoor and outdoor environments (Aguilar-Santana et al., 2020; Cuce & Cuce, 2019; Simões et al., 2023). The values of both SHGC and U-value have a notable impact on the heat gains or losses experienced in the room, thereby influencing the energy consumption associated with heating, ventilation, and air conditioning (HVAC) systems. In addition to thermal parameters, the optical performance of transparent photovoltaics also encompasses factors such as visual light transmittance (VLT) and glare probability value (D. Liu et al., 2020; X. Liu

& Wu, 2022). These optical properties have a direct impact on both the visual experience inside the building and the energy consumption of artificial lighting.

The impact of BIPV adoption on building energy consumption is illustrated in Figure 2. Indoor illumination and artificial lighting in buildings are influenced by the optical characteristics of BIPV windows, thus affecting energy consumption for lighting. The thermal characteristics of BIPV windows, as expressed by the SHGC and U values, directly impact indoor heat gain and consequently energy consumption for air conditioning. BIPV windows have the capability to generate electricity, which can be consumed within the buildings or fed into the grid, thereby contributing to building energy conservation to a certain extent. Therefore, the impact of BIPV windows on building energy consumption is determined by the trade-off between lighting performance, electrical generation performance, and thermal performance.

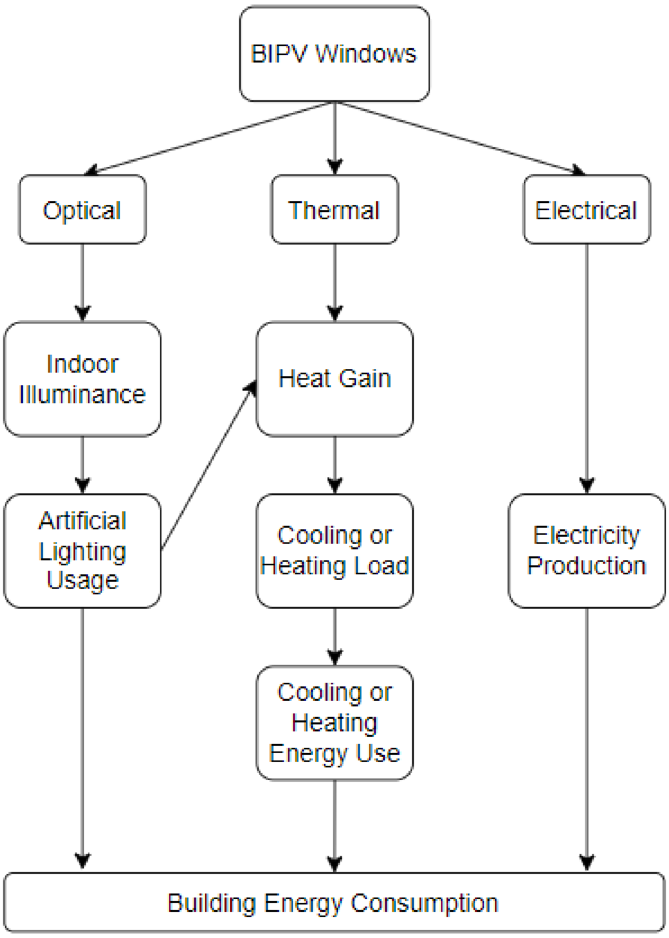

Figure 2. The impact of BIPV adoption on building energy consumption (Ng et al., 2013).

To enhance the VLT of the entire glazing system, the solar cells usually do not cover the entire surface area of the glazing. The ratio of the area covered with solar cells to the total area of the glazing is referred to as the cell coverage ratio. This type of BIPV windows has the capability to generate electricity while simultaneously reducing indoor solar heat gain by converting a portion of the incident radiation into electrical energy.

2.2 Model Development

The study was carried out through the development of a model utilizing OpenStudio and the execution of EnergyPlus simulations based on version 23.1. The model featured a room geometry measuring 5 m × 5 m × 3 m, which is depicted in Figure 3. The non-transparent facade material of the building consisted of brick walls, maintaining consistency across all simulations. The sole distinction within the simulations pertained to the window type, comparing a 0.6 mm clear glass window with a semi-transparent photovoltaic (PV) window model. The specifications for each window type are presented in Table 1 for clear glass and Table 2 for the PV windows. By comparing and contrasting the outcomes of both scenarios, the analysis aimed to ascertain the profiles of energy consumption and the potential for energy savings.

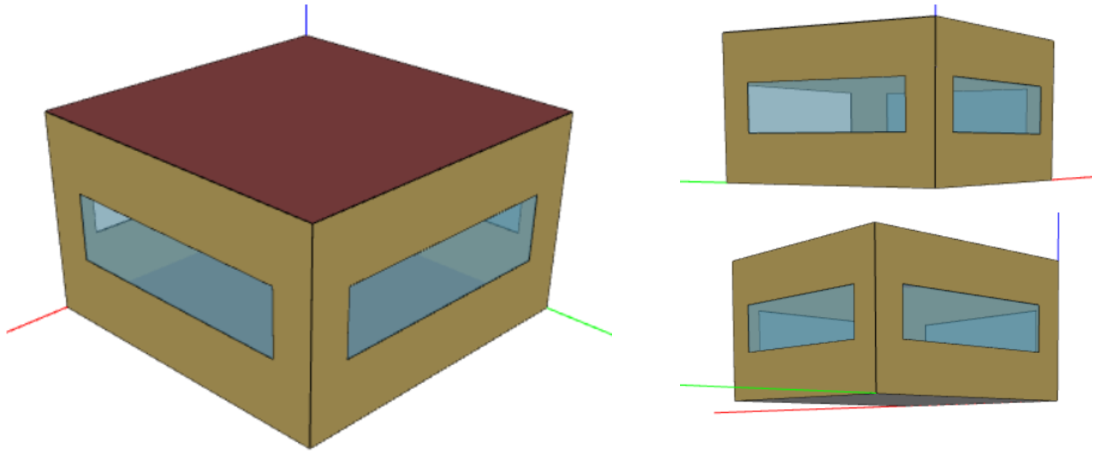

Figure 3. Building model used in this study.

Table 1. Specifications for clear glass used in this study.

Parameter(s)	Specification
Thickness	0.006 m
Solar Transmittance	83.7%
Visible Transmittance	89.8%
Conductivity	0.9 W/mK

Table 2. Specifications for PV Windows used in this study.

Parameter(s)	Specification
PV Type	aSi
U-Factor	5.03 W/m^2K
Solar Heat Gain Coefficient	0.4002
Visible Transmittance	24%
Cell Efficiency	2.4%

In order to assess the energy efficiency of transparent photovoltaics applied to building windows in a tropical climate, a systematic approach was employed. The initial phase encompassed the creation of a detailed model utilizing OpenStudio, facilitating a comprehensive depiction of the building's geometric attributes, encompassing dimensions and layout. Subsequently, EnergyPlus simulations were conducted on this model, employing predefined climate profiles to accurately simulate the diverse environmental conditions. This investigation involved simulations performed in a tropical climate, using five distinct climate profiles: Jakarta, Indonesia; Singapore, Singapore; Kuala Lumpur, Malaysia; Rio de Janeiro, Brazil; and Kotoka, Ghana. These weather profiles are described in Table 3.

Subsequently, the specifications for building materials were established, ensuring the constancy of all other variables except for the window type. This enabled a direct juxtaposition between a conventional transparent glass window and a semi-transparent photovoltaic window. The material used in the building model is described in Table 4.

Table 3. Climate profile used in this simulation.

City, Country	Average Temperature	Maximum Dry Bulb Temperature	Minimum Dry Bulb Temperature
Jakarta, Indonesia	28.0 °C	35.0 °C	22.0 °C
Singapore, Singapore	28.3 °C	31.4 °C	22.0 °C
Kuala Lumpur, Malaysia	28.2 °C	36.0 °C	22.0 °C
Rio de Janeiro, Brazil	24.7 °C	39.6 °C	12.5 °C
Kotoka, Ghana	27.9 °C	34.9 °C	19.0 °C

Table 4. Material used in the study model.

Building Component	Material
Roof	Plasterboard + Clay Tile
Ceiling	Plasterboard + Concrete + Porcelaine
Wall	Air Film + Cement Plaster + Brick + Cement Plaster + Air Film
Floor	Porcelain Floor + Concrete
Door	Wooden door
Window	1) a-Si Photovoltaic 2) Clear Glass

Each building material used has its own material characteristics, including thermal transmittance and solar transmittance. These characteristics are input into a building model with transparent windows and compared with windows with transparent photovoltaics, within the specific context of building windows in a tropical climate.

3. Results and Discussions

3.1 Simulation Results and Analysis

The simulation results, which are succinctly illustrated in Figure 4, shed light on the energy consumption profiles associated with the different window options. The total and net-site energy is a crucial metric that encompasses the comprehensive energy consumption of a building, encompassing both the energy utilized within the building and the energy losses during distribution. Total energy refers to the overall energy utilized within a building, encompassing all forms of energy consumption. On the other hand, net-site energy accounts for the difference between the energy consumed within the building and the total energy generated on-site.

In comparison to clear glass windows, PV windows have better material qualities that block the entry of solar radiation, reducing the need for room cooling. The analysis conducted on the provided data demonstrates that PV windows generally exhibit slightly lower total site energy compared to clear glass windows across all evaluated cities, as shown in Figure 4(a). For instance, Jakarta has the highest total site energy consumption across both clear glass and BIPV categories, with values of 8.48 GJ and 8.39 GJ, respectively. On the other hand, Rio de Janeiro exhibits the lowest energy consumption figures across both glazing types, with total site energy values of 5.68 GJ and 5.58 GJ. Several factors influence these results, especially related to the capacity of glazing materials to mitigate solar radiation, including aspects such as glazing thickness, conductivity, solar heat gain coefficient, solar transmittance, visible transmittance, and U-factor which are different between clear glass and PV windows, where PV windows block light and heat slightly better than clear glass (Cuce & Cuce, 2019; Romaní et al., 2021; Wheeler et al., 2022). This indicates that the integration of PV windows has the potential to contribute to a reduction in the overall energy demand of a building, thereby enhancing energy efficiency.

Furthermore, as in Figure 4(b), when considering net site energy, which accounts for energy production within the buildings, Jakarta also exhibits the highest values among the cities, with 8.48 GJ for clear glass and 4.94 GJ for BIPV. On the other hand, Rio de Janeiro exhibits the lowest energy consumption figures across both glazing types, with total site energy values of 5.68 GJ and 5.58 GJ and net site energy of 5.68 GJ and 2.31 GJ for clear glass and BIPV, respectively. The results obtained from the data analysis indicate that PV windows show significant reductions in net site energy compared to clear glass windows.

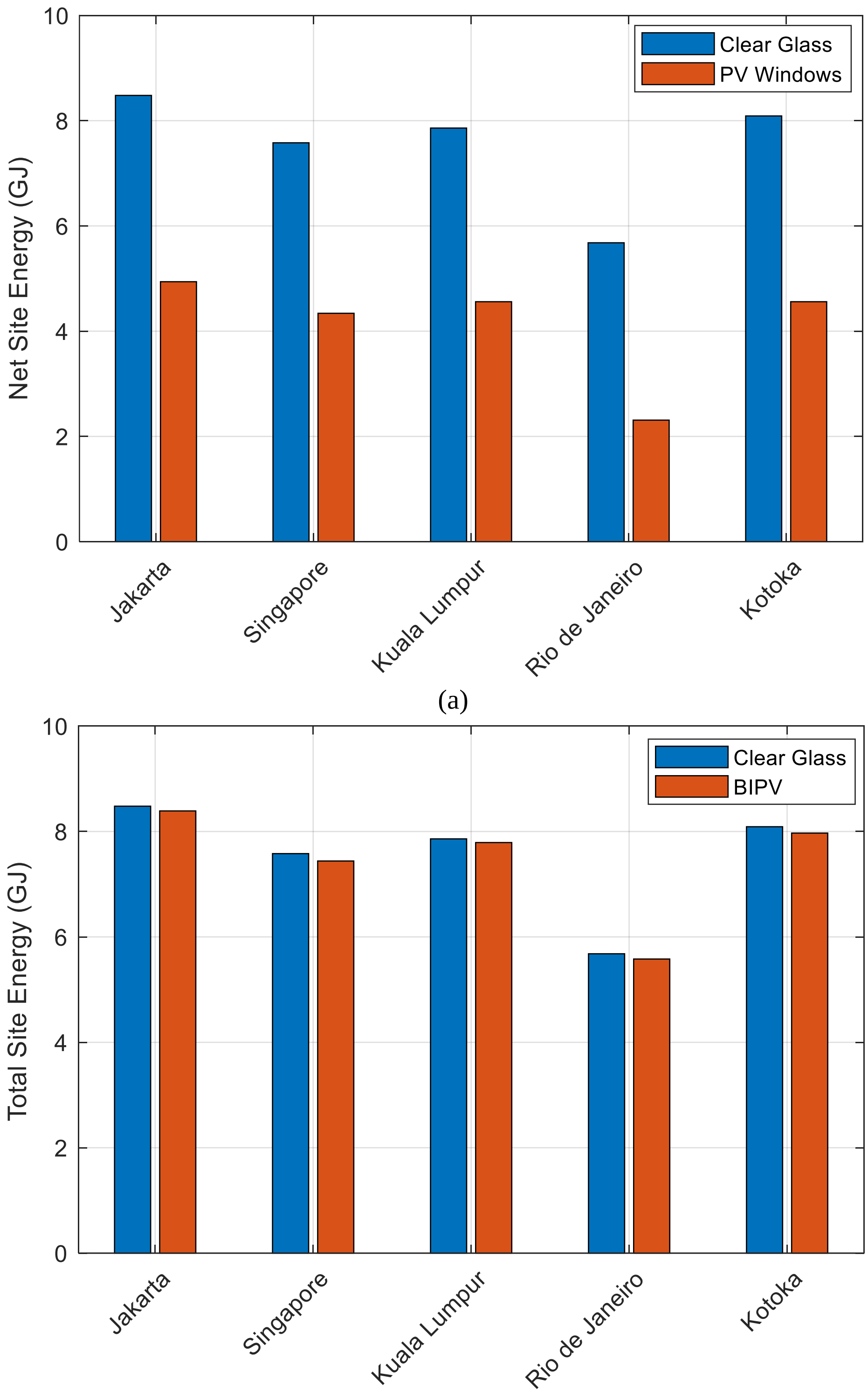

Figure 4. Comparison of clear glass and PV windows in several tropical cities in the terms of (a) Total Site Energy and (b) Net-Site Energy.

The energy performance and potential energy savings are influenced by various factors, including the climatic profiles of the evaluated cities. The climate profiles play a significant role in determining the heat load imposed on the building and the potential energy generation capacity of PV windows. In practice, the benefits of PV windows can be most pronounced in climates characterized by, for example, sunlight and high solar radiation, find optimal use in cities like Jakarta, Singapore, and Kuala Lumpur. The city's tropical climate, characterized by abundant sunlight throughout the year, creates ideal conditions for PV technology to harness solar energy efficiently. Key climate variables such as solar irradiance, ambient temperature, and cloud cover play an important role, with higher solar irradiance levels and moderate temperatures increasing PV performance. As a result, PV windows will work as effective solutions for reducing energy consumption in buildings in regions characterized by these climatic profiles.

Additionally, the percentage decrease in energy consumption and losses provided by PV windows can be observed across the analyzed cities, with Jakarta experiencing a reduction of approximately 41.72% in net site energy, while Rio de Janeiro witnessed a decrease of approximately 59.30% in net site energy. These percentages signify the significant impact of PV window integration in achieving energy efficiency and emphasizing their potential benefits for reducing energy consumption in building applications.

These results support the findings of previous studies conducted in other tropical regions. For example, Hassan et al (2022) concluded that the use of Semi-Transparent Photovoltaics on windows of buildings in Dhaka and Abu Dhabi would be more effective in reducing energy demand by approximately 40–65%, compared to their use in Oslo, where they only decrease energy demand by 25–35%.

3.2 Discussions

The development of PV windows in tropical countries faces unique climate challenges. Tropical regions have high solar radiation levels, offering great potential for PV window applications (Hassan et al., 2022; Joseph et al., 2019). However, the hot and humid climate presents difficulties in managing temperature and ensuring thermal stability. Elevated temperatures can negatively impact the efficiency and performance of PV materials, leading to decreased power output (Dubey et al., 2013; Ebhota & Tabakov, 2023; Ye et al., 2013). Moreover, the high humidity levels can affect the durability and lifespan of PV windows, necessitating advanced materials and design strategies to ensure their effectiveness in such environments (Hasan et al., 2022; Segbefia et al., 2021). Addressing these climate challenges is crucial to maximize the potential of PV windows in tropical countries and ensure their long-term viability.

Policies and regulations play a crucial role in facilitating the adoption and incorporation of renewable energy technologies, including PV windows. However, specific policy frameworks tailored to PV window applications may still be lacking or insufficiently developed in many tropical countries (Kılıç & Kekezoğlu, 2022; Lo et al., 2018; Lu et al., 2020; Tarigan, 2020; Vaka et al., 2020). It is imperative to establish supportive policies that incentivize the utilization of PV windows, such as implementing feed-in tariffs, offering tax incentives, and formulating building codes that promote their integration into building designs (Dijkgraaf et al., 2018; Duque et al., 2017; Halimatussadiah et al., 2023; Le et al., 2022; Panagiotidou et al., 2021). Furthermore, the formulation of clear guidelines and standards for PV window installations is essential to ensure safety, performance, and interoperability (Kim et al., 2016; Needell et al., 2021). By bolstering policy support and creating an enabling environment for PV window technologies, the widespread deployment of such systems can be facilitated, contributing significantly to the transition toward sustainable and energy-efficient buildings.

One of the significant obstacles encountered in the development of PV windows in tropical countries pertains to achieving seamless architectural integration. It is imperative that PV windows not only serve as energy-generating components but also meet the aesthetic and functional requirements of building designs (X. Liu & Wu, 2022; Mesloub et al., 2020; Ulavi et al., 2014; Yang et al., 2023). Striking a balance between energy performance, visual transparency, and architectural aesthetics poses a substantial challenge in the advancement of PV windows. Integrating PV technology into various window types, such as operable windows, skylights, and curtain walls, demands meticulous design considerations and engineering solutions to uphold functionality, durability, and overall building performance (T. Chen et al., 2022; Martín-Chivelet et al., 2022; Rababah et al., 2021; Yu et al., 2021). Overcoming these challenges associated with architectural integration will be crucial in ensuring the widespread acceptance and adoption of PV windows in tropical countries.

Moreover, the successful integration of PV windows into building designs necessitates a multidisciplinary approach. Collaboration among architects, engineers, material scientists, and other relevant stakeholders is vital to optimizing the architectural integration of PV windows (Fregonara et al., 2013; Rifaat, 2019). This collaborative effort entails exploring innovative design strategies, such as incorporating advanced materials, optimizing the arrangement of PV cells within the windows, and implementing smart control systems for efficient energy management. Additionally, considering factors such as daylighting, glare control, thermal insulation, and structural stability becomes essential to maintain occupant comfort and ensure the overall performance of the building (Buratti et al., 2018; Huang et al., 2012; Kolani et al., 2023; Mannan & Al-Ghamdi, 2021). By addressing these architectural integration challenges through interdisciplinary collaborations and innovative design approaches, PV windows can be seamlessly incorporated into building designs, leading to enhanced energy efficiency and aesthetics in tropical countries.

4. Conclusions

The use of BIPV in transparent building facades presents numerous advantages, notably in enhancing energy efficiency. However, the extent of potential energy savings varies across different cities, emphasizing the effectiveness of PV windows in improving energy efficiency and minimizing energy losses during distribution. Tropical countries have a greater potential to utilize BIPV to reduce energy demand in buildings, thereby enabling the creation of net zero energy buildings. However, the potential benefits of BIPV in tropical countries have not been extensively explored, and our study aims to fill this gap by estimating the energy efficiency benefits derived from using transparent photovoltaics in buildings located in Jakarta, Singapore, Kuala Lumpur, Rio de Janeiro, and Kotoka. Our analysis results indicate that the benefits are particularly evident in tropical regions, characterized by consistent solar radiation and a high demand for cooling. This situation presents the potential to substantially reduce net energy consumption, with our findings showing reductions of up to 59.3% in a building model located in Rio de Janeiro.

The energy-saving benefits of BIPV systems are significantly influenced by climate-related challenges, including temperature and humidity management. Increasing these energy savings necessitates the adoption of advanced materials and design strategies. Our research findings provide valuable data that serve as a foundation for promoting the widespread adoption of BIPV technology. To overcome policy challenges should implement supportive policies, incentives, and clear guidelines for the installation of PV windows. These measures can help to create an enabling environment for the uptake of BIPV systems and accelerate their deployment in various regions.

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